Observations and Modeling of Low-Altitude Ionospheric Responses to the 2017 September X8.2 Solar Flare at Mars

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Introduction & Motivation

- Main source of dayside ionosphere at Mars:
  - Solar EUV (10-100 nm), creating M2 layer
  - X-ray (< 10 nm), creating M1 layer
- Dayside ion production mainly comes from two processes:
  - I. Initial photoionization from photons, creating ions and photoelectrons
  - II. Electron impact ionization (EII) by photoelectrons

- Solar EUV and X-ray irradiance vary orders of magnitude during a flare, causing variations in ionosphere/thermosphere
  - September 10, 2017, MAVEN encountered the largest flare (X8.2) to date
  - Characterizing ionosphere variation

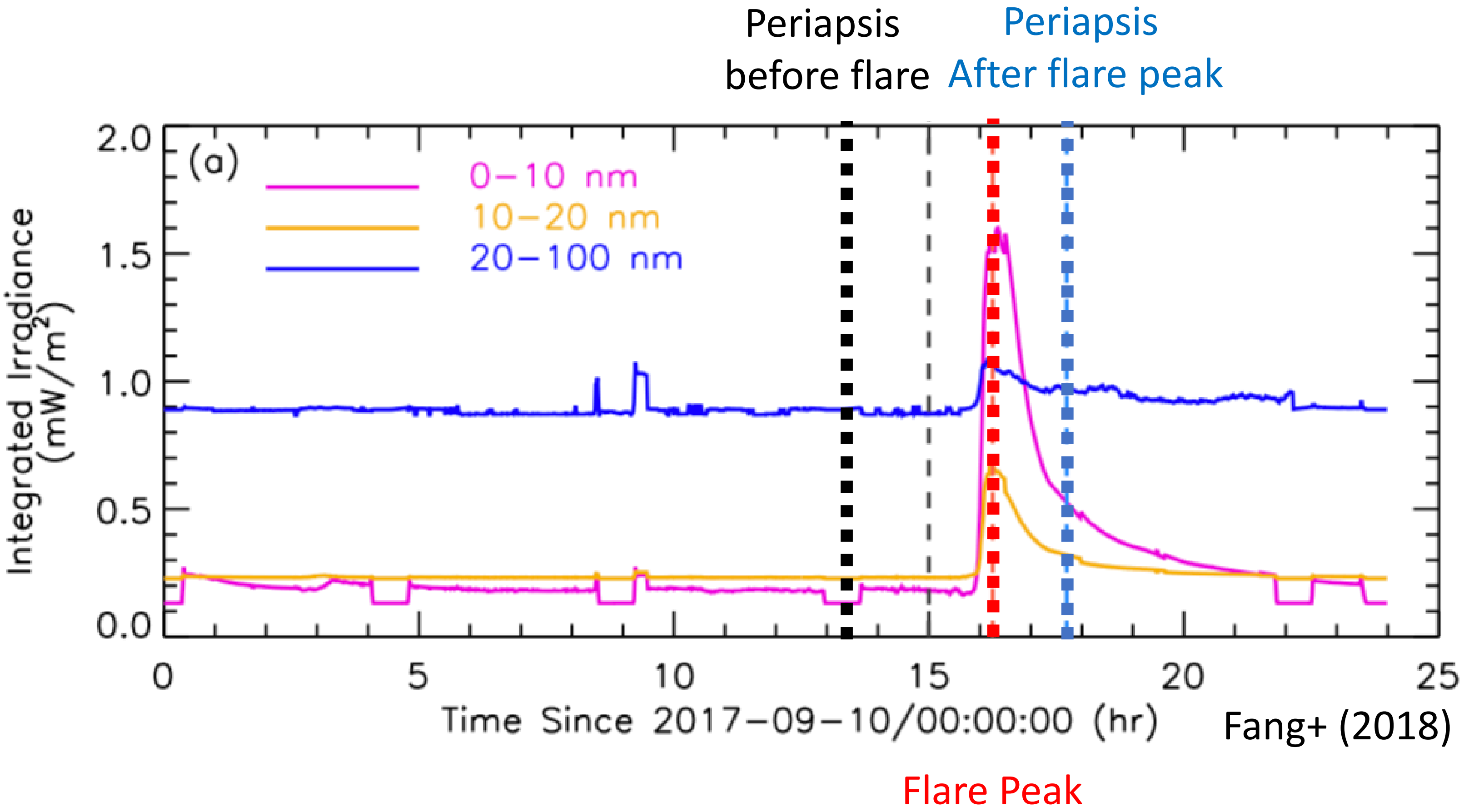
Methodology

- Characterizing low-altitude ionospheric response to this flare with SuperThermal Electron Transport (STET) model:
  - Modeling photoelectron flux variations
  - Calculating <u>photoionization rate</u> and <u>EII rate</u> for ion production
  - Assuming photochemical equilibrium (PCE, <200 km): obtain O_2^+ and CO_2^+ densities

- STET solves superthermal electron flux $\boldsymbol{\psi}$ in time (t), spatial distance along a single magnetic field (s), electron energy (*E*), and pitch angle $\boldsymbol{\mu}$:

$$\frac{\beta}{\sqrt{E}}\frac{\partial\psi}{\partial t}+\mu\frac{\partial\psi}{\partial s}-\frac{1-\mu^2}{2}\left(-\frac{F}{E}+\frac{1}{B}\frac{\partial B}{\partial s}\right)\frac{\partial\psi}{\partial\mu}+EF\mu\frac{\partial}{\partial E}\left(\frac{\psi}{E}\right)=Q+S_{ee}+\sum_{\alpha}\left(S_{e\alpha}+S_{e\alpha}^{*}+S_{e\alpha}^{+}\right)+\sum_{i}\left(S_{ei}+S_{ei}^{*}+S_{ei}^{-}\right)$$

Methodology

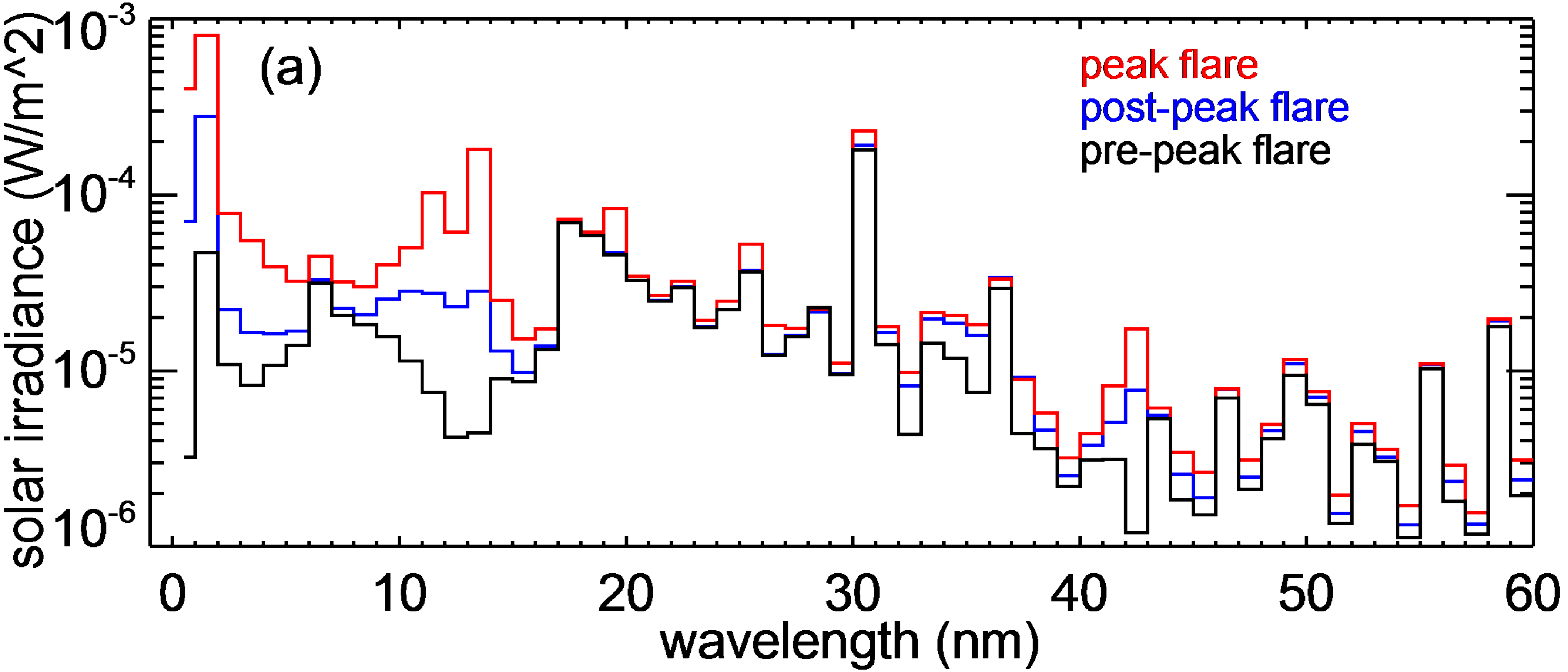


Fang+ (2018)

- Overview of the flare event
- Three periods are selected: pre-flare, peak-flare, post-peak flare

Methodology

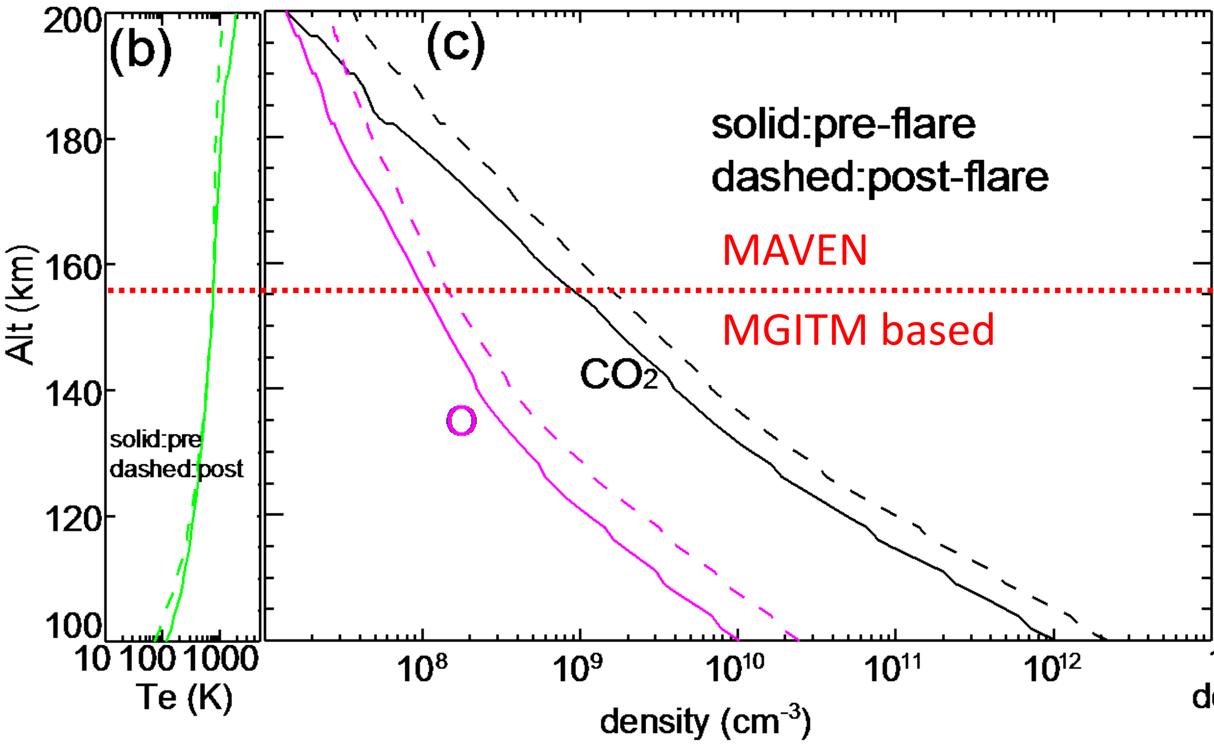
- EUV inputs to STET:
    - EUV spectra from a spectral model [Thiemann et al., 2018], similar to FISM



Methodology

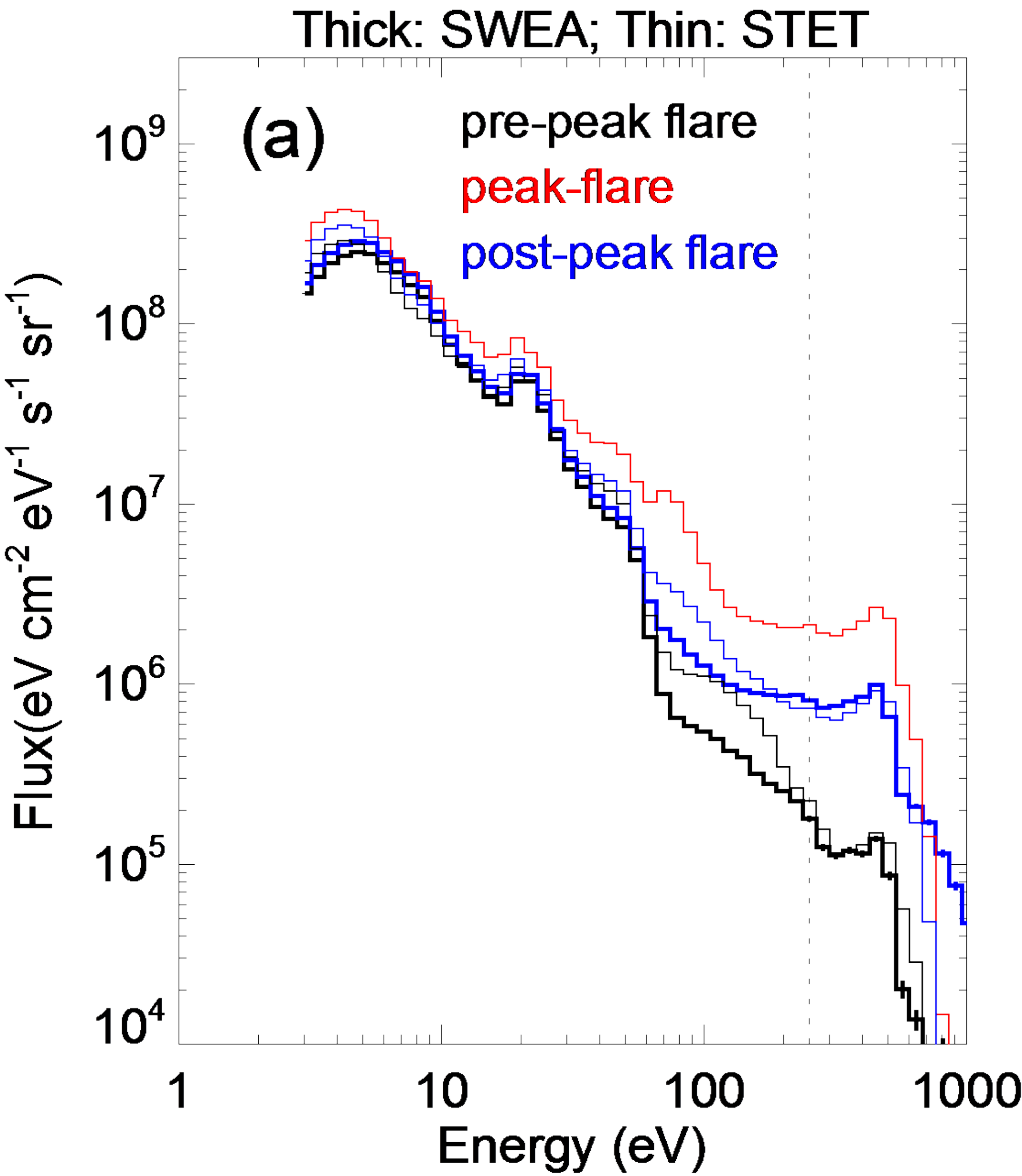
- Main inputs to STET:
  - O and CO_2 density from NGIMS (Neutral Gas and Ion Mass Spectrometer) & MGITM (Mars-Global Ionosphere Thermosphere Model) for below and above MAVEN periapsis, respectively
  - Te from LPW (Langmuir Probe and Waves), extrapolated to neutral Tn at 115 km from MGITM

- Only TWO Neutral and thermal plasma available:
  - Pre-flare and peak-flare: pre-flare profiles
  - Post-peak flare: post-peak profiles



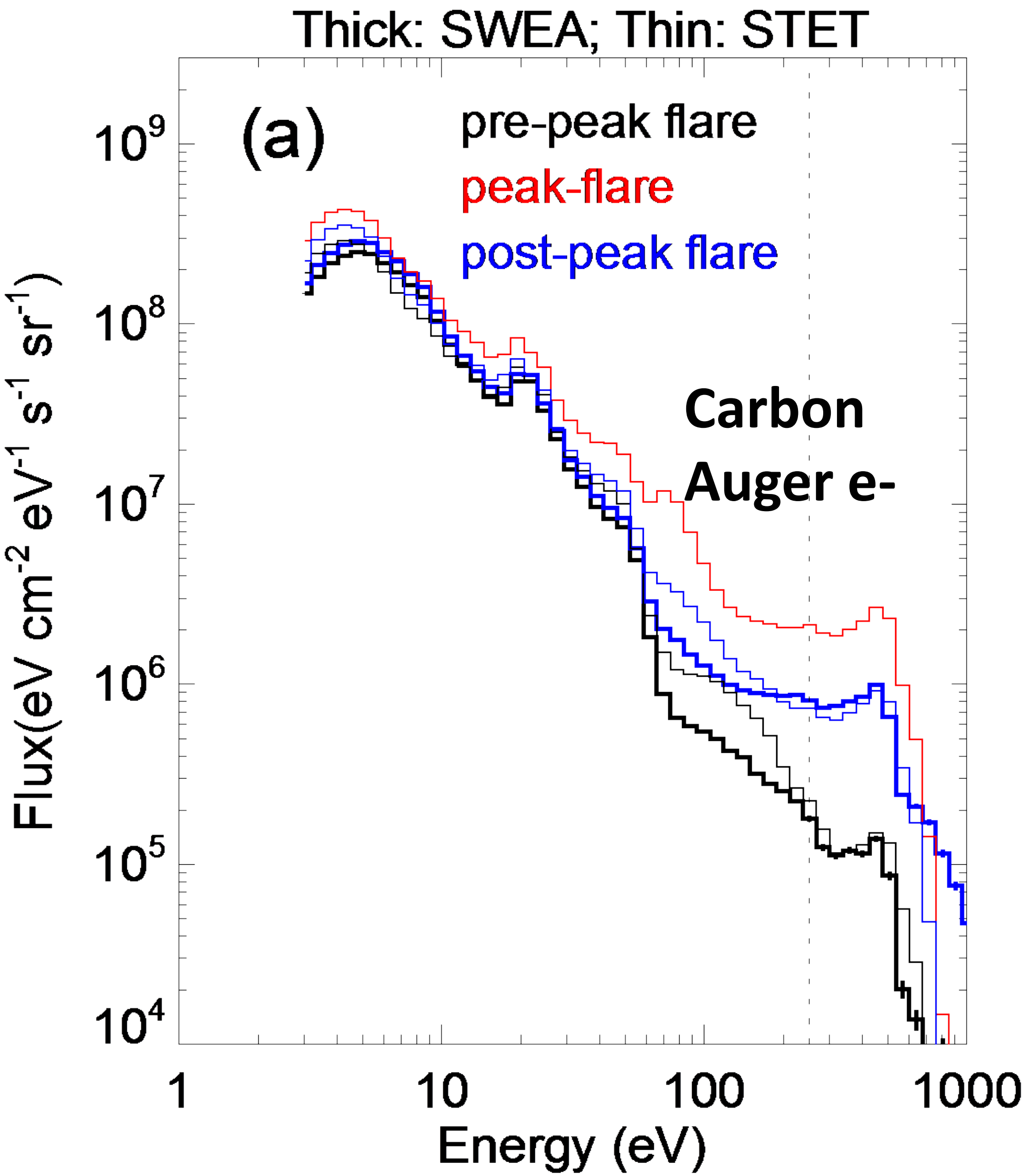
Data-Model Comparison of Photoelectron Spectra

- **Thick** black and blue energy spectra from SWEA (Solar Wind Electron Analyzer) observations
- Thin black, blue, and red energy spectra from STET modeling
- Typical ionospheric photoelectron spectral features: He-II peak, knee, O Auger peak
- Mostly in good agreement
  - Within 30% for < 60 eV and 200-500 eV
  - Modeled solar irradiance spectra are very accurate for EUV & X-ray ~17-60 nm, 1-6 nm, correspondingly



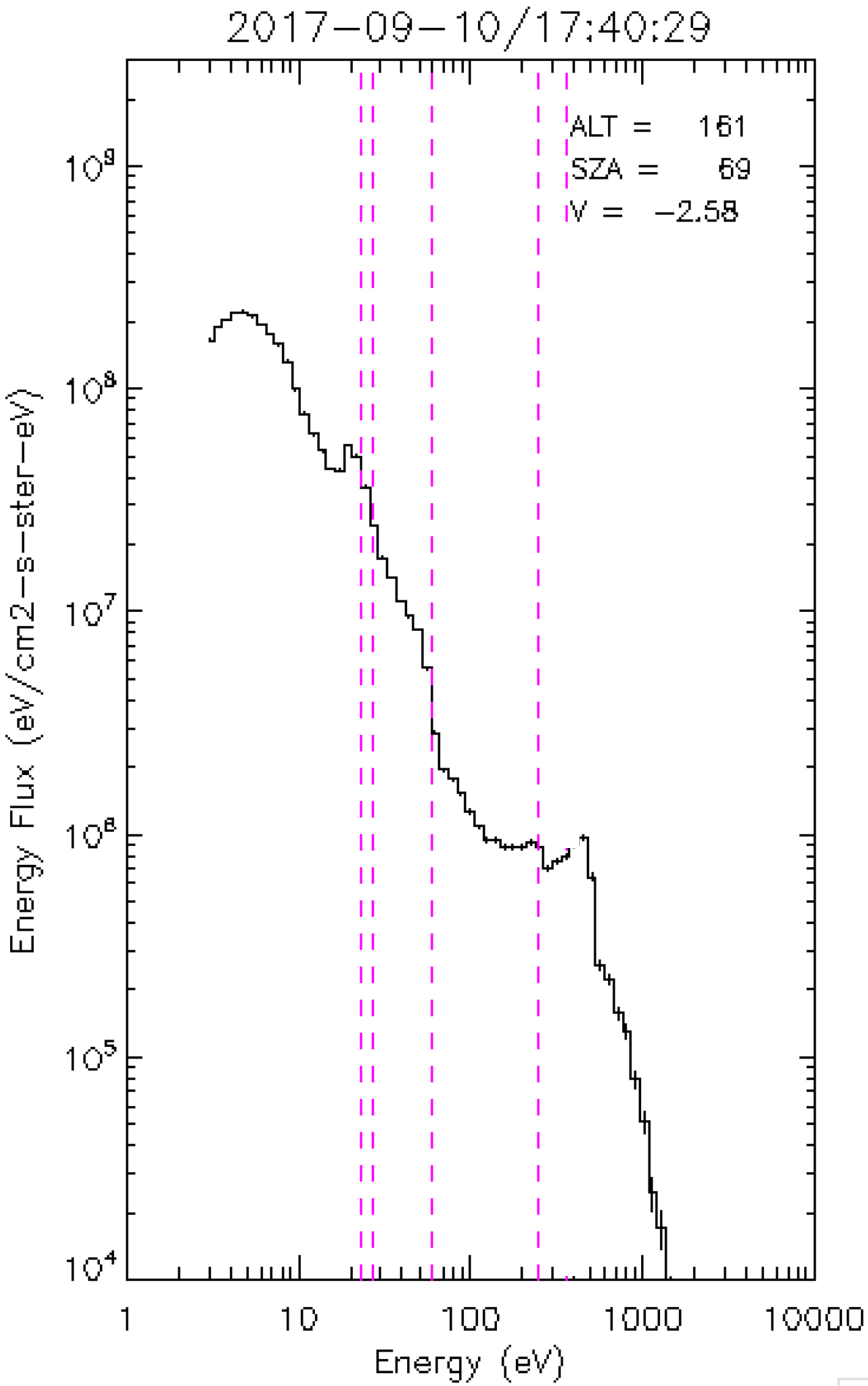
Data-Model Comparison of Photoelectron Spectra

- Auger electrons
  - Soft X-ray ionizing inner-shell electrons of C, O, N
  - Resultant ions deexciting through emitting Auger electrons
  - At fixed energies: C~250 eV, N~360 eV, O~500 eV
- C Auger electron peak in both modeled and observed photoelectron spectra
  - Being consistently observed over 4 min during this flare event



A Clearer Example of Carbon Auger Electrons From SWEA

- This provides a clear and unambiguous identification of the carbon Auger peak in the electron energy spectra in the Martian ionosphere for the first time.



Observations and Modeling of Plasma Densities

- Ion Densities calculated assuming photochemical equilibrium:

R1: $CO_2 + h\nu \rightarrow CO_2^+ + e$ **[STET]**

R2: $CO_2^+ + O \rightarrow CO + O_2^+;\ k_2 = 1.64\times 10^{-10}$

R3: $CO_2^+ + O \rightarrow CO_2 + O^+;\ k_3 = 9.6\times 10^{-11}$

R4: $O^+ + CO_2 \rightarrow O_2^+ + CO;\ k_4 = 1.1\times 10^{-9}$

R5: $CO_2^+ + e \rightarrow CO + O;\ k_5 = 4.2 \times 10^{-7}\ (300/Te)^{0.75}$

R6: $O_2^+ + e \rightarrow O + O;\ k_6 = 2.4 \times 10^{-7}\ (300/Te)^{0.7}$

$CO_2^+ + O$ ----> $O_2^+ + CO$
Source for O2+
Loss for CO2+, depending on n(O)

Schunk and Nagy [2009]

- From R1-R6, we can obtain:

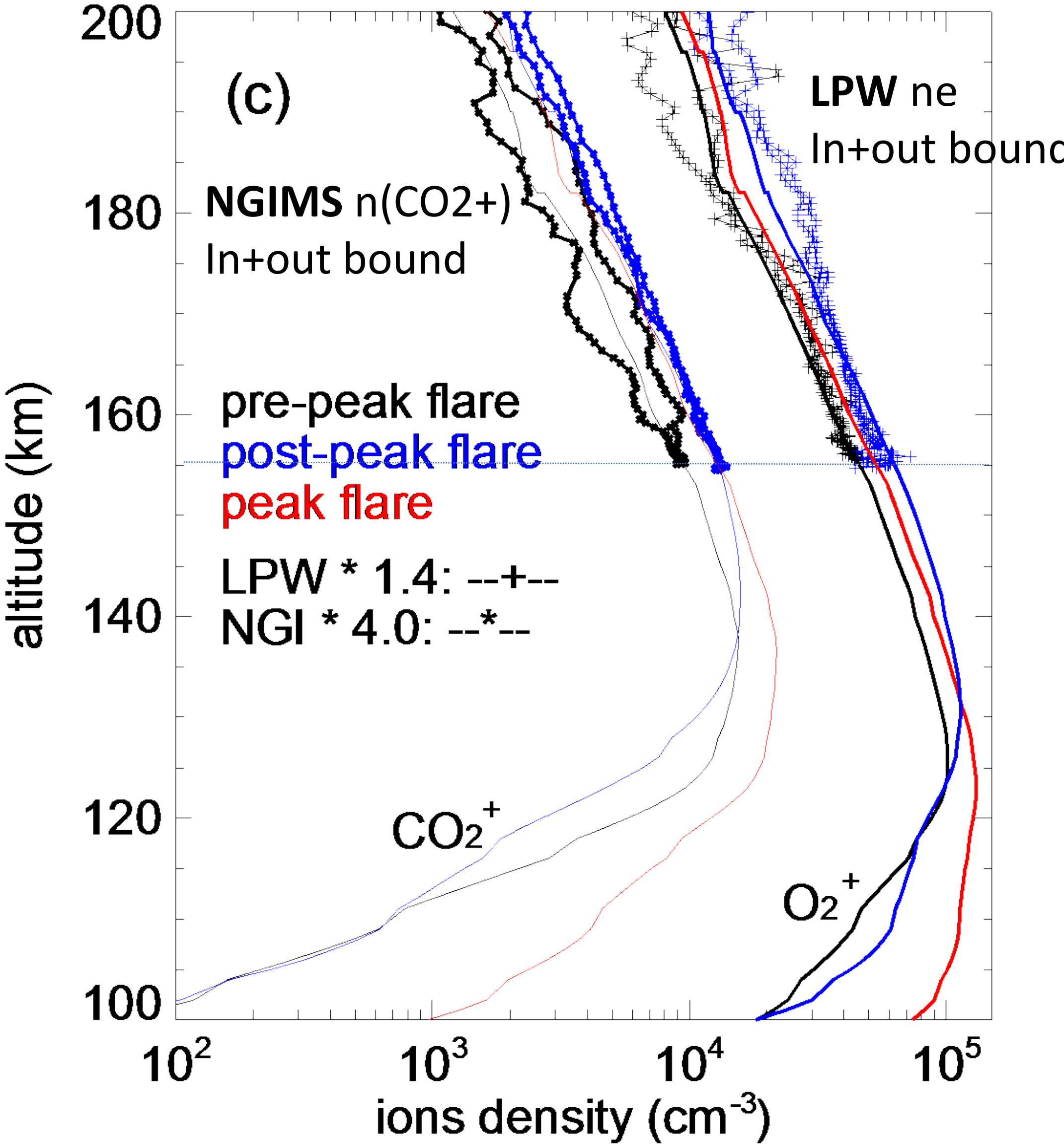
$$n(O_2^+) = \sqrt{(k_2 + k_3)n(CO_2^+)n(O)/k_6}$$ (R2, R3, R4, R6)

$$n(CO_2^+) = \frac{P(CO_2^+)}{(k_2 + k_3)n(O) + k_5 n(O_2^+)}$$ (R1, R2, R3, R5)

Observations and Modeling of Plasma Densities

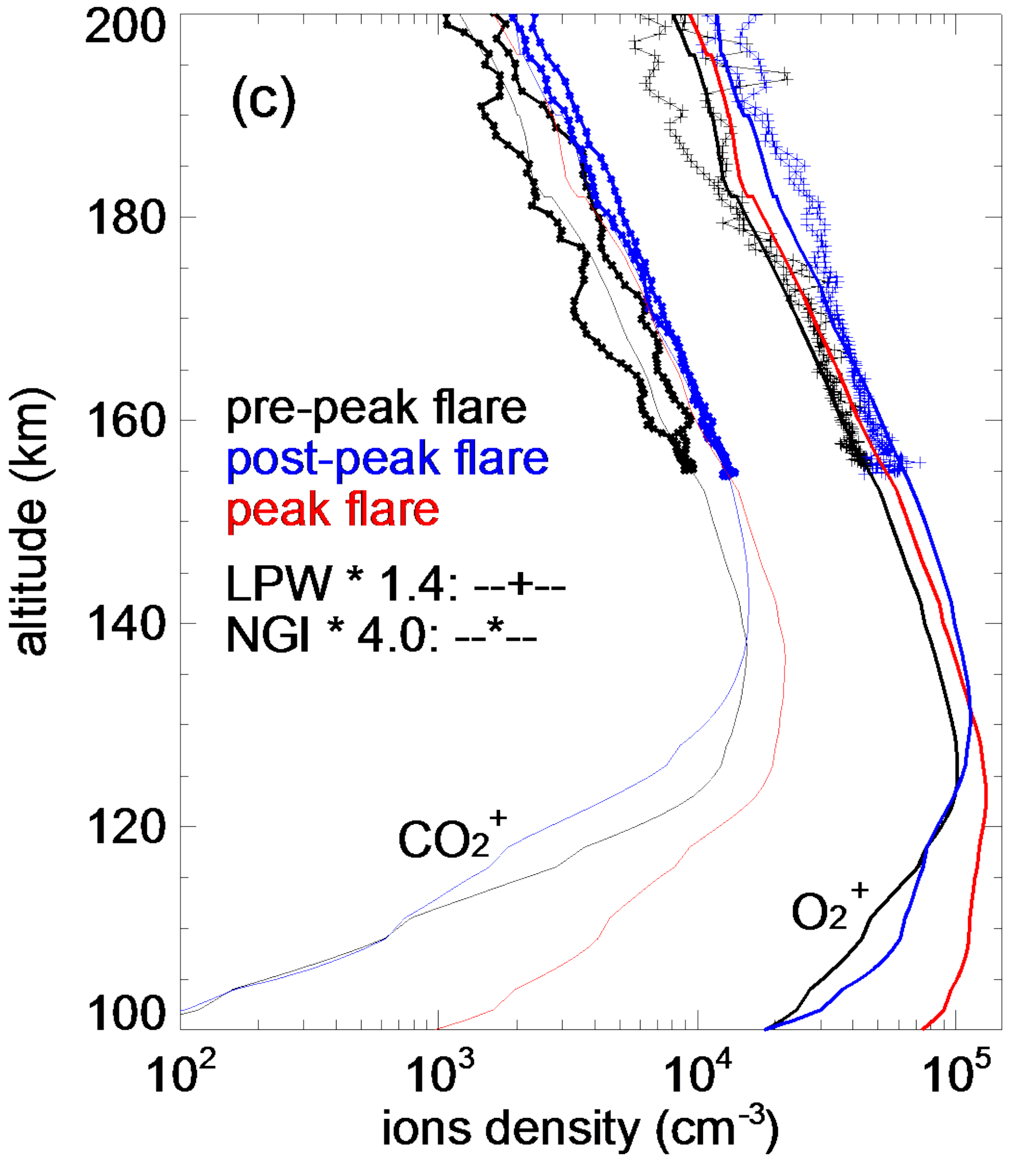
- From model:
    - Solid lines: CO2+ and O2+ densities for 3 periods

- From observations:
    - LPW e- density (*1.4) and NGIMS CO2+ density (*4) for pre-flare and post-peak flare, inbound and outbound



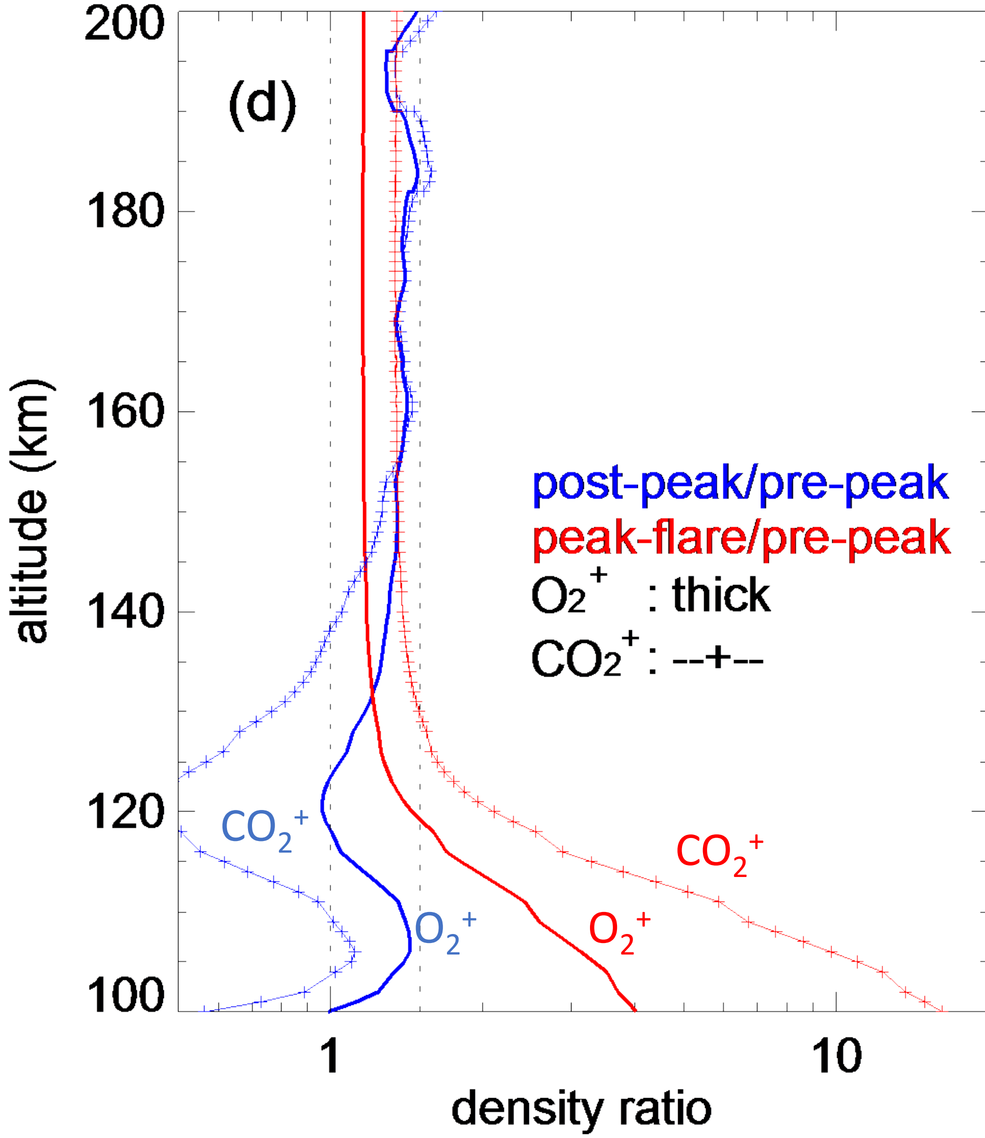
Observations and Modeling of Plasma Densities

- Comparison of modeled ion densities and observations:
  - ☞ Modeled O_2^+ densities ~40% higher than LPW e- density, reasonable agreement
  - Modeled CO_2^+ densities ~4x NGIMS n(CO_2^+)
  - ☞ The relative enhancement are similar, comparing MAVEN and model results
  - ☞ Similar scale heights from MAVEN and model



Observations and Modeling of Plasma Densities

- Relative density enhancement to the pre-flare period from modeling:
  - Peak-flare/pre-peak
    - atmosphere profiles kept the same
    - N(O_2^+): ~15% increase for M2 layer and up to ~300% for M1 layer; ~sqrt(prod. rate)
    - N(CO_2^+): ~35% increase for M2 layer and up to ~1500% for M1 layer; ~prod. Rate
  - Post-peak flare/pre-peak
    - thermosphere expansion modulates ion enhancements
    - N(O_2^+): <50% enhancement
    - N(CO_2^+): <50% enhancement above 140 km; *decrease* below 140 km due to enhanced O density (loss rate)



Summary

- Modeling low-altitude ionospheric response to X8.2 flare with STET
- Found a good agreement between modeled (STET) and measured (SWEA) photoelectron spectra, meaning small errors in modeled EUV/X-ray spectra
- First clear and repeated identification of the carbon Auger peak in the Martian ionosphere
- Comparing pre-flare and flare peak, for the same atmosphere profiles, the modeled O_2^+ and CO_2^+ densities are increased by 15% and 35% above the M2 peak and up to 300% and 1500% at 100 km, respectively
- Comparing pre-flare and post-peak flare period, O_2^+ and CO_2^+ density enhancement < 50%, consistent with MAVEN observations, due to a combination of increased EUV fluxes and also neutral atmosphere expansion
  - A higher O density during the flare actually results in decreases in CO_2^+ density below 140 km

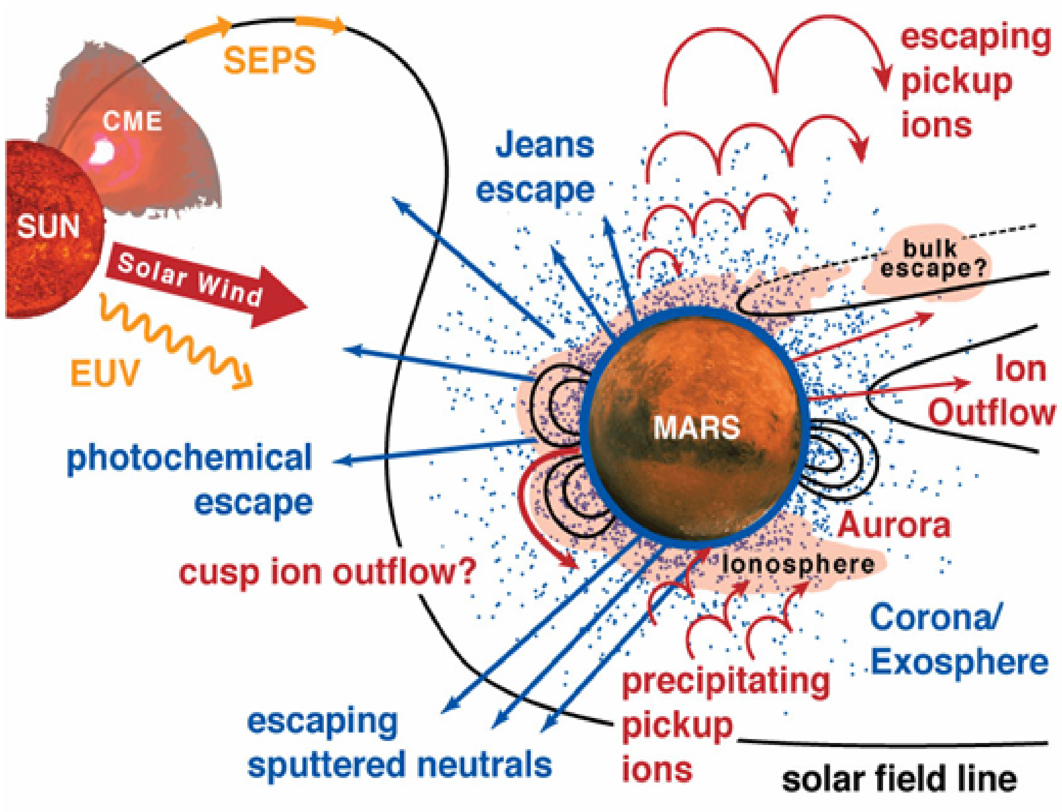
MAVEN Instruments

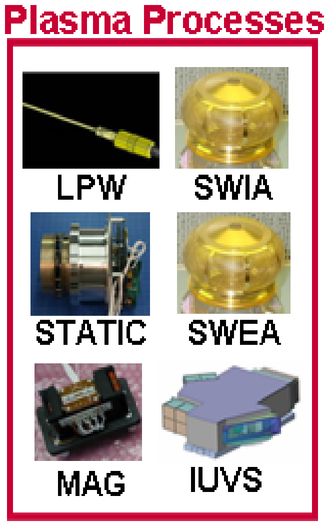
EUVM:

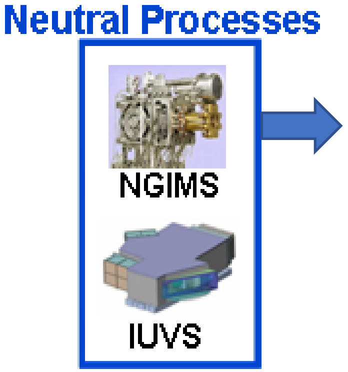
- 0-7 nm, 17-22 nm, 121-122 nm, 3 bands
- Drive an irradiance model

Ne, Te

Suprathermal e- (photoelectron) measurements







Neutral densities (O, CO2)
Ion density (CO2+)

Methodology

- Main inputs to STET:
  - O and CO_2 density from NGIMS (Neutral Gas and Ion Mass Spectrometer) & MGITM (Mars-Global Ionosphere Thermosphere Model)
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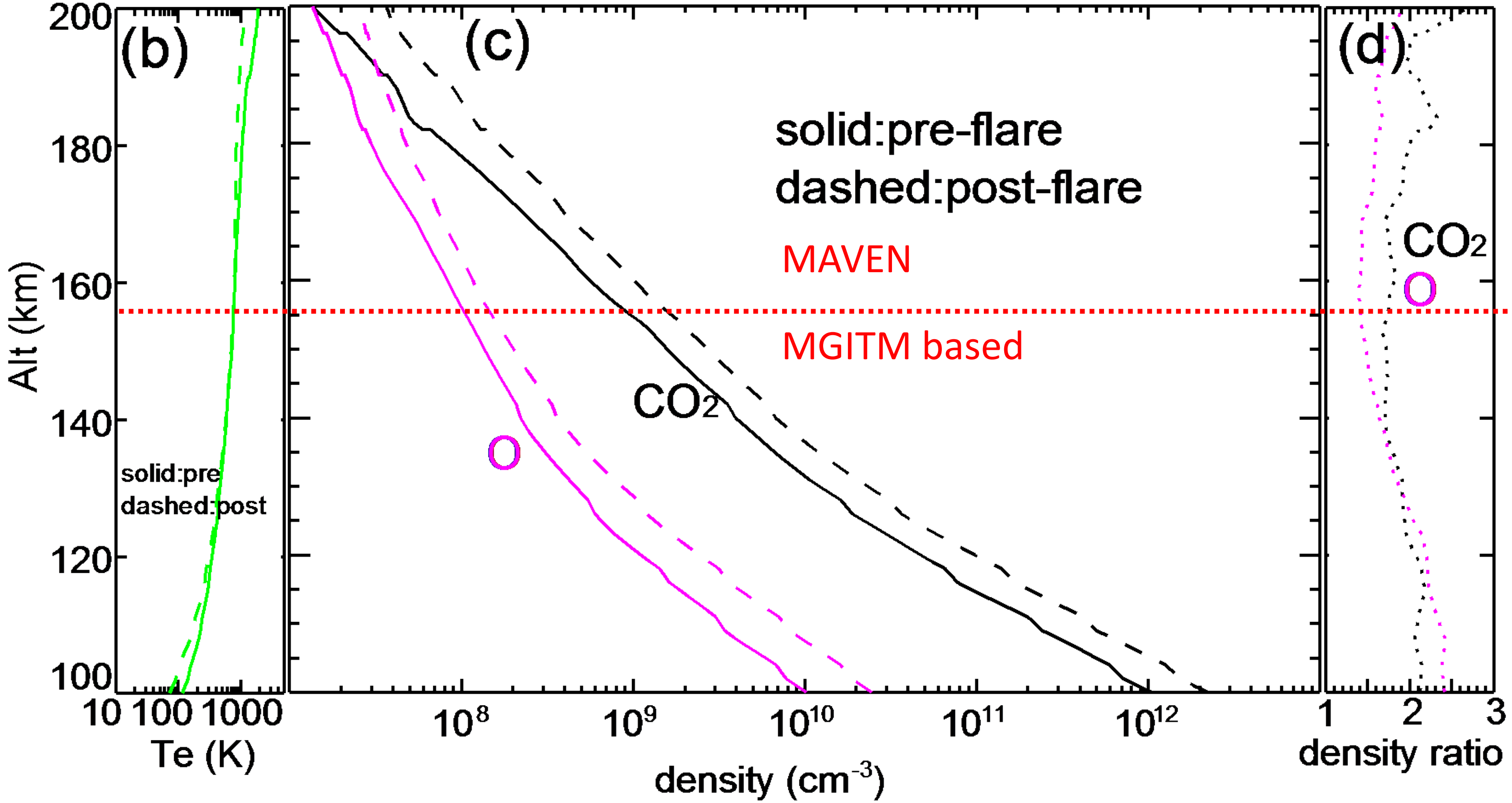
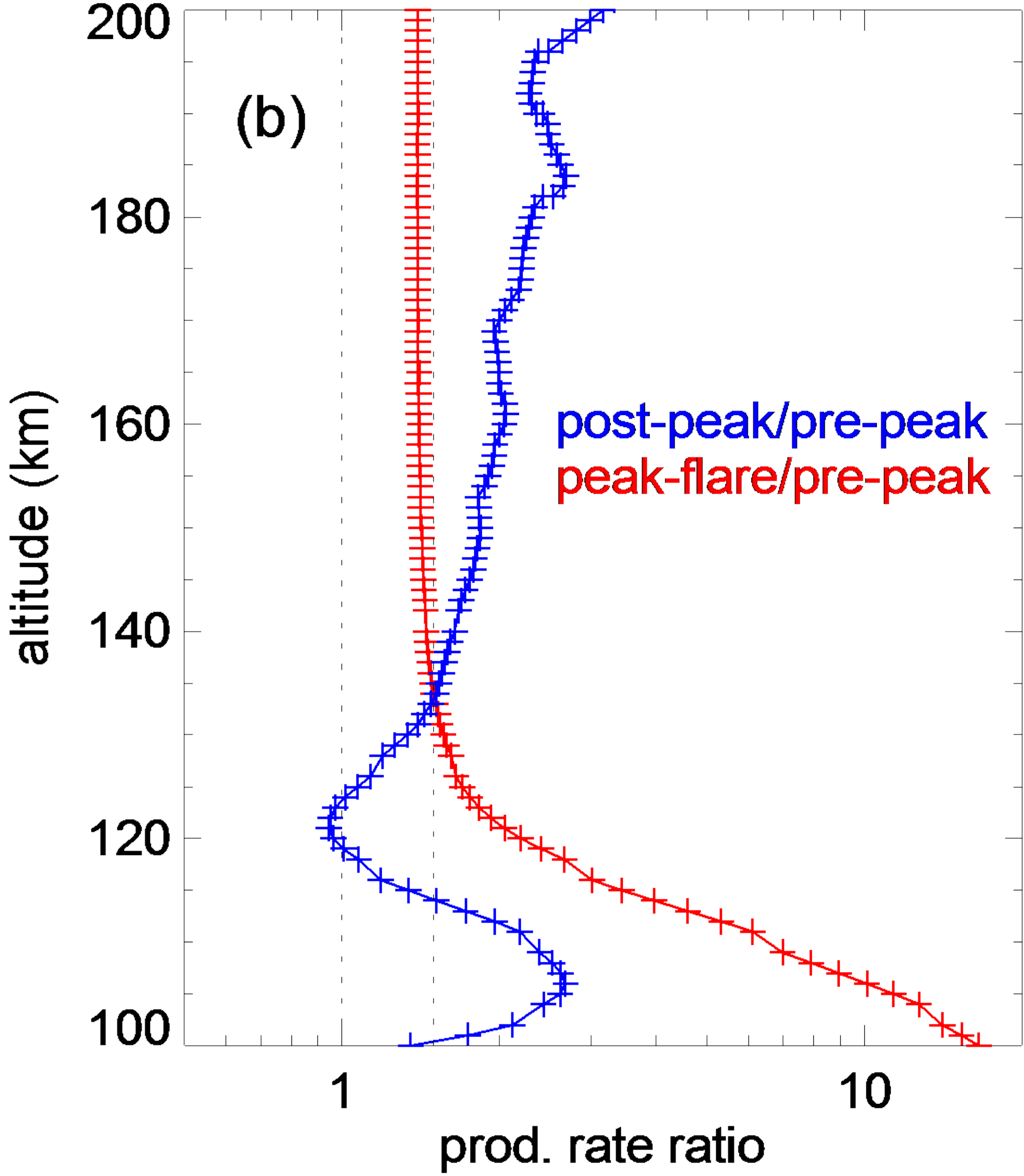


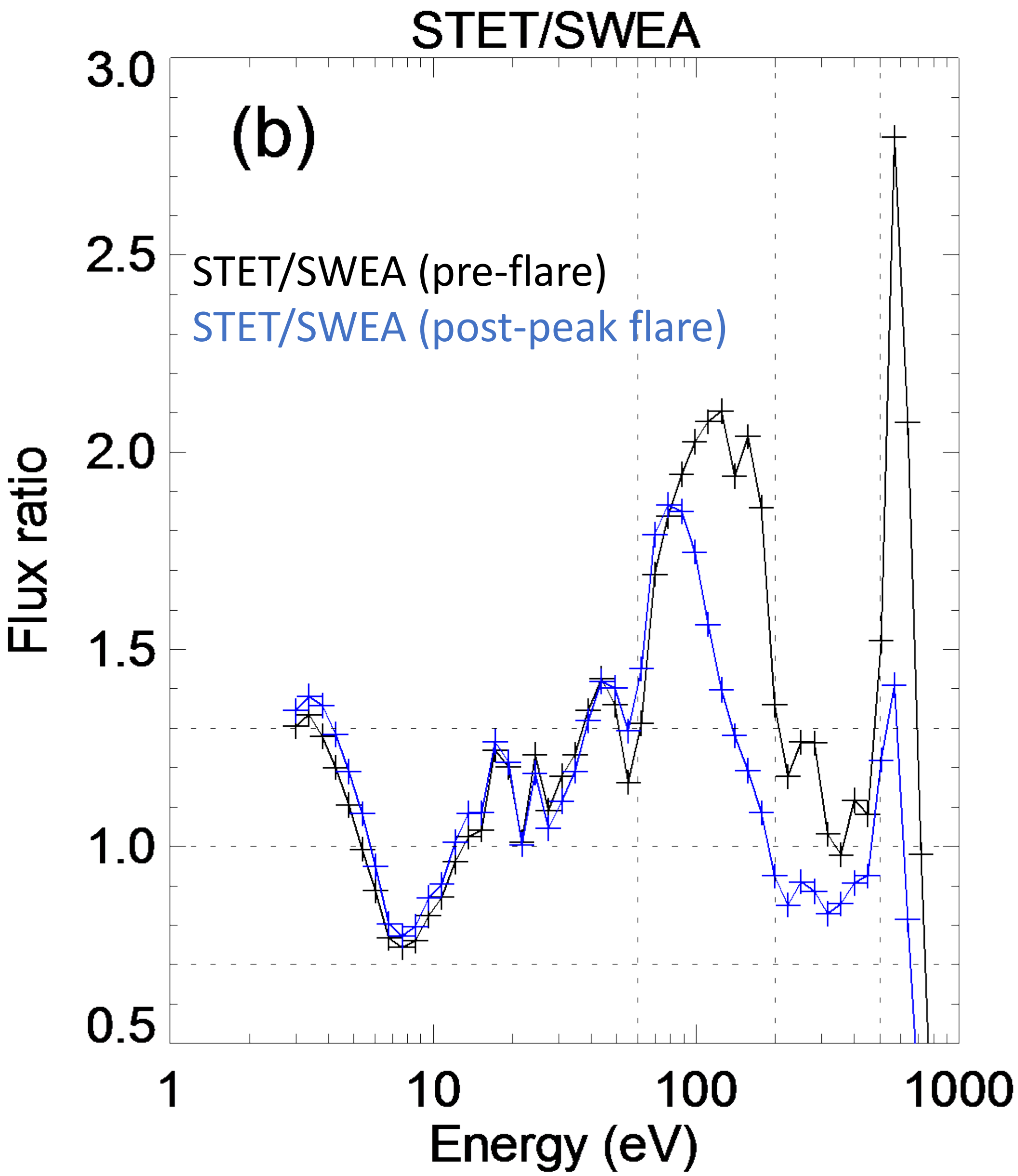
- Only TWO Neutral and thermal plasma available:
  - Pre-flare and peak-flare (the same): pre-flare MAVEN measurements and MGITM results
  - Post-peak flare: post-peak MAVEN measurements and MGITM results

Observations and Modeling of Plasma Densities

- Relative enhancement in total production (photoi + EII):
  - Peak flare/pre-flare: increased 40% above 130 km and up to 1500% down below 130 km (same atmosphere)
  - Post-peak flare/pre-flare: < 200% due to enhanced solar irradiance and expanded thermosphere



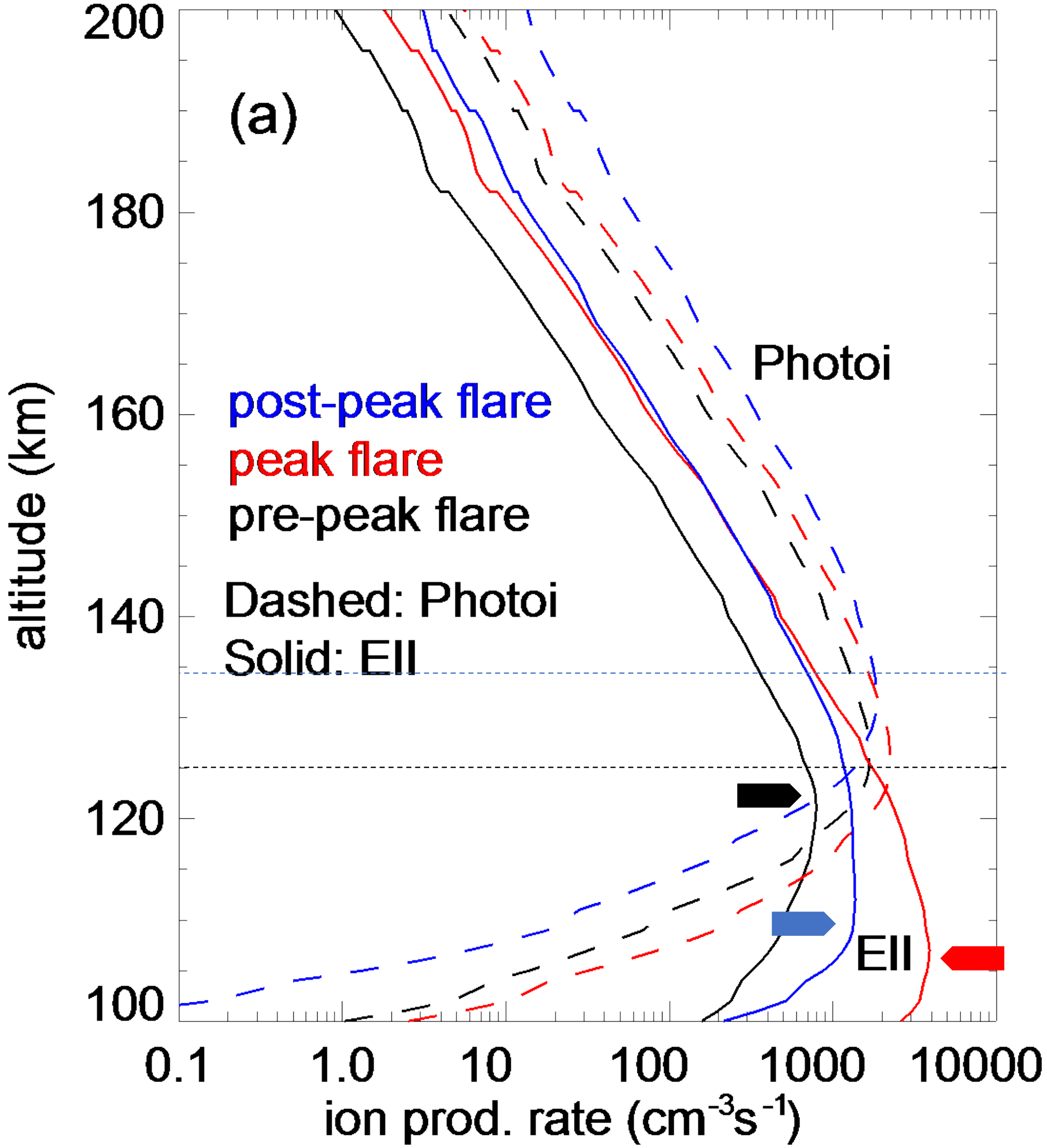
Data-Model Comparison of Photoelectron Spectra



- Quantitative comparison:
  - (b) Within 30% for < 60 eV and 200-500 eV, roughly corresponding to EUV & X-ray ~17-60 nm, 1-6 nm

Observations and Modeling of Plasma Densities

- Production rates for CO_2^+ :
  - PHI (photoionization): dashed lines
    - peaks ~125 km from pre-flare and peak-flare, as the two using the same background profiles
    - peaks ~135 km for post-peak, due to expanded thermosphere
  - EII (electron impact ionization): solid lines
    - peaks deeper, from pre-peak, post-peak flare to peak-flare, as the soft X-ray spectrum becomes harder
- Relative enhancement in total production (PHI + EII):
  - Peak flare/pre-flare: increased 40% above 130 km and up to 1500% down below 130 km (same atmosphere)
  - Post-peak flare/pre-flare: < 200% due to enhanced solar irradiance and expanded thermosphere



Observations and Modeling of Plasma Densities

- The M2 layer peaks ~ 125 km for O2+ and ~140—150 km for CO2+
- A shoulder from the M1 layer is seen in O2+ profile for the post-peak flare period, but not for the pre-flare and peak-flare periods
    - Whether M1 and M2 peaks are well separated depends on solar spectral shapes and neutral density profiles